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SEARCH FOR SUPER EARTHS BY TIMING OF TRANSITS WITH COROT

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Abstract. We explore the possibility of detecting Super Earths via transit timing variations with the satellite *CoRoT*.

1 Introduction

The satellite *CoRoT* (Baglin et al., 2006) was launched on 27th December 2006 with a double scientific purpose: the analysis of stellar seismology and the detection of extrasolar planets by the method of transits. So far, 7 transits have been published (see Jean Schneider's Extrasolar Planets Encyclopaedia¹), but more will come in the near future. Table 1 gathers the data from these six planets and one brown dwarf. *CoRoT*'s photometric precision is below $8 \cdot 10^{-4}$ in 2h at $R = 15$ (Aigrain et al., 2009) and candidates are found with transit depths of 0.034% (Leger et al., 2009). Neptune size planets seem to be common (Gould et al., 2006) and, there is something even more interesting: they don't come alone (Mayor et al., 2009). Super Earths, which should also be numerous, are in the range of detectability of *CoRoT* (Leger et al., 2009; Queloz et al., 2009). In the near future the number of candidates will increase and we will find ourselves with a collection of planets whose diversity we can only start to imagine.

Section 2 is a short introduction to the *CoRoT* mission. Section 3 gives a short overview of different sources of transit timing variations which could allow the detection of Super Earths with the satellite *CoRoT*.

2 CoRoT

CoRoT is an afocal telescope with a 27 cm diameter pupil, equipped with 4 CCDs (2048×2048 pixels each); the pixel scale is $2.32''$ and the field of view is

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¹<http://exoplanet.eu>

$3.05^\circ \times 2.8^\circ$. The selection of observational targets follows two different strategies: the seismology channel observes a small number (10) of bright stars ($6 < m_v < 9$) with a cadence of 32s whereas the exoplanet channel observes a large number ($\sim 11\,000$) of faint stars ($12 < m_v < 16$) every 512s (although a limited number of targets is measured every 32s). *CoRoT* is placed in a polar low Earth orbit which determines the observational scheme. The satellite continuously monitors the same region of the sky during 150 days; but then it has to turn around to avoid the Sun entering the field of view: these are the *long runs*. Immediately before or after the turnaround, the satellite is pointed during roughly 20 days to perform a *short run* in a different direction. Every year, *CoRoT* observes 2 long runs and 2 short runs providing roughly 40 000 light curves. These light curves are narrowed down in the search for transits and a list of candidates is built. The most promising candidates are followed up photometrically and spectroscopically from the ground.

The photometric follow-up attempts to discover if the transit is on target or, on the contrary, if it is produced by a background binary. The PSF of *CoRoT* is quite large: the flux for each star is calculated on-board in masks of size 60 pixels on average. In front of the CCD there is a prism used to produce chromatic light curves with the aim of distinguishing between stellar (coloured) activity and (achromatic) transits. However, for faint stars it is not possible to make this distinction. Large masks raise the probability of observing background binaries, which are a major source of confusion (Pont et al., 2005).

Spectroscopic follow-up measures the mass of the transiting object. There is a degeneracy between the mass and the radius of low mass stellar objects, brown dwarfs and planets (see Fig. 1); to confirm the nature of a transiting object it is mandatory to perform radial velocity measurements and calculate the object's mass. This can become a bottleneck for the characterization because the measurement of faint candidates is challenging.

Deleuil and Baglin (2008) is a very interesting short summary of *CoRoT* and its achievements. Fully detailed recent information about the technical characteristics of the mission can be found in Fridlund et al. (2006); Barge et al. (2008b) and Drummond et al. (2008).

3 Transit Timing Variations

Kepler's laws of motion assign periodical orbits to planets. However, there are numerous sources of perturbations which produce deviations from the periodicity. Not only are there differences in the observed minus calculated (O–C) epochs of transits, but also in their durations and depths. Some possible sources are general relativity effects, the quadrupolar moment of the gravitational potential of the star, tidal interaction or even the proper motion of the star (Miralda-Escudé, 2002; Jordán and Bakos, 2008; Pál and Kocsis, 2008; Rafikov, 2009). But all these perturbations act on timescales much longer than the baseline of *CoRoT* observations and so, in spite of their interest, are beyond the scope of this study.

However, there are still several other sources of perturbations acting on shorter

Table 1. 5 transits found by *CoRoT*.

	1b ^a	2b ^b	4b ^c	5b ^d	6b ^e	7b ^f	3b ^g
radius (Jupiter's radii)	1.49	1.47	1.19	1.39	1.15	0.15	1.01
mass (Jupiter's masses)	1.03	3.31	0.72	0.47	3.3	0.015	21.66
period (days)	1.51	1.74	9.20	4.04	8.89	0.85	4.25

^aBarge et al. (2008a).^bAlonso et al. (2008); Bouchy et al. (2008); Alonso et al. (2009).^cAigrain et al. (2008); Moutou et al. (2008).^dRauer et al. (2009).^eFridlund (2009).^fLeger et al. (2009); Queloz et al. (2009).^gDeleuil et al. (2008).

timescales, such as those produced by other planets (Schneider, 2004; Holman and Murray, 2005; Agol et al., 2005; Nesvorný and Morbidelli, 2008), Trojan planets (Laughlin and Chambers, 2002; Dvorak et al., 2004; Ford and Holman, 2007), moons (Doyle and Deeg, 2004; Kipping, 2009a,b), orbital eccentricity (Kipping, 2008) and the light time effect, the so-called LITE (widely studied in binary systems, see Irwin 1952; Mayer 1990; Borkovits et al. 2003). In addition to these, Winn (2009) contains a very interesting list of the information that can be obtained from transits.

3.1 Photometric Precision

From Doyle and Deeg (2004), we can calculate the maximal accuracy of δt_0 that one can achieve when determining the position of a transit of length T_{tr} and depth ΔL ; the photometric accuracy is δL and the number of observations is N . This accuracy is:

$$\delta t_0 = \delta L \frac{T_{tr}}{2\Delta L \sqrt{N}}.$$

In *CoRoT*, with a photometric accuracy of 0.1%, measuring a transit of depth 1% at the observing cadence of 32s, we can achieve a timing accuracy on the order of seconds.

3.2 Multiple Systems

On the day this manuscript was submitted, there were 374 extrasolar planets known, among which most are isolated. But there are already 40 known multiple planet systems and in the future, as Dr. Udry pointed out in this conference, probably more and more planets will be found in multiple systems. See also the work by Dr. Wright in this volume.

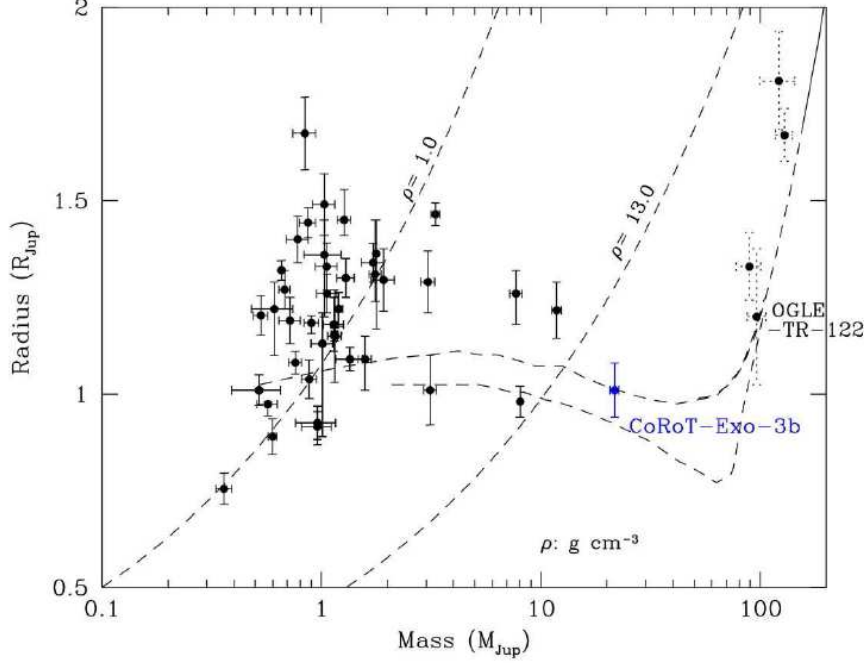


Fig. 1. Figure from Deleuil et al. (2008) showing the mass–radius diagram for planets and low mass M stars. CoRoT-3b is highlighted. The theoretical isochrones at 10 and 1 Gyr are from Baraffe et al. (2003).

We can calculate the perturbations in the time of arrival of the transit signal of a planet if there is another planet in the system in an interior orbit. Rigorous calculations are done in Agol et al. (2005), but we can estimate δt , the amplitude of this perturbation, with the expression:

$$\delta t = \frac{P_e}{2\pi} \frac{m_i}{m_* + m_i} \frac{a_i}{a_e}; \quad (3.1)$$

where P stands for period, m for masses, a for the semi-major axis of the orbits and the subscripts i and e refer to the inner and outer (exterior) planet respectively. For a Jupiter outer planet with a period of 20 days around a star of one solar mass, an interior Super Earth of 11 terrestrial masses would produce a perturbation of 3 seconds, which is within the limits of *CoRoT*.

Dynamics in multiple planets systems is a complicated matter (for example see, in this volume, the work by Dr. Michtchenko) and resonances are one of the most important features because they enhance the amplitude of these perturbations and could open the door to the discovery of low mass planets (Holman and Murray,

2005; Haghighipour et al., 2007).

In 2008 alone, at least 8 publications have seen the light on the detection of this kind of perturbation: Agol et al. (2009); Alonso et al. (2009); Díaz et al. (2008); Hrudková et al. (2009); Irwin et al. (2008); Miller-Ricci et al. (2008a,b); Shporer et al. (2009).

3.3 Trojan planets

In our Solar System, Trojan satellites are a group of asteroids moving close to the Lagrange points L4 and L5 in 1:1 mean-motion resonance with Jupiter's orbit. Many efforts have been done in the search for these kind of objects in extrasolar systems (see for example Moldovan and Matthews 2008 and Madhusudhan and Winn 2009). Bodies in these orbits are stable (Ford and Gaudi, 2006; Dvorak et al., 2004) and can be found not only photometrically or by radial velocity, but also by the timing variations that they produce in the transits of the planet whose orbit they share. We can estimate the amplitude of this perturbation:

$$\delta t = \frac{M_{Trojan}}{M_{planet}} \frac{\alpha}{2\pi} P_{planet}; \quad (3.2)$$

for a Trojan object with the mass of the Moon and a transiting planet with the mass of Jupiter in a 20 day orbit, α being the typical angle involved in the calculation, with $\alpha \sim 30$ degrees (see the references given above for justification), the amplitude of the perturbation is about 5 seconds. Needless to say, if the transiting planet is a Super Earth, this perturbation is far more important. Another speculative hypothesis is the existence of massive Trojan planets. If the ratio between the mass of the transiting planet plus the mass of the Trojan over the mass of the star is below $\sim 1/27$, the system can be stable; this opens the possibility of Trojan Super Earths (see Nauenberg 2002; Schwarz et al. 2007 and references therein).

3.4 LITE

LITE was first used by the astronomer Ole Römer, working in Paris Observatory with Jean-Dominique Cassini, to measure the speed of light (Römer, 1676). Nowadays it is used to find hidden companions to binary systems, even those of planetary mass (Deeg et al., 2008; Lee et al., 2008). But we can find the same effect in multiple planet systems (Schneider, 2005). The reflex motion induced in our Sun by Jupiter has an amplitude of one solar radius, which light covers in 2 seconds. If we observe the transits of an inner planet and there is an outer planet in the system, the amplitude of the LITE perturbation is:

$$\delta t = 2 \frac{m_e}{M_*} \frac{a_e}{c}; \quad (3.3)$$

which is of the order of 0.1 seconds for the time baselines of *CoRoT* (and in this case, we must concede that this favors the detection of high mass companions and not of Super Earths).

3.5 Moons

No moon has yet been detected around any extrasolar planet, although their existence is expected (Sartoretti and Schneider, 1999). However, their detection is difficult (Brown et al., 2001). In general, it is not an easy task to estimate the magnitude of the perturbation because it depends on the orbit of the satellite around the planet; and for planets within the specific period range detectable by *CoRoT*, we don't yet have any clue as to how much this estimate may be. Nevertheless, reasonable assumptions in the general case give perturbations under 1 s, which is below *CoRoT* limits.

However, we point out the possibility of finding binary planets (Cabrera and Schneider, 2007). Binarity is common among stars, from bright massive objects down to brown dwarfs; and we can also find binary objects from the size of trans-neptunian objects down to asteroids. Binarity should be possible among planets and those systems will produce peculiar transit signals.

4 Conclusions

The photometric precision achieved by *CoRoT* allows the detection of Super Earth planets in transit; but here we have shown that also non-transiting Super Earths could be detected in multiple systems by the perturbations they might produce in transiting planets. We have shown several possible scenarios and discussed their limitations.

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